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Selection of Confluence Sites with Ice Problems for Structural Solutions

Andrew M. Tuthill and Anthony C. Mamone

March 1997

Abstract: This study examines a broad range of ice problems at river confluence sites, grouping the sites into four categories. Weighted criteria were used to select two representative sites from each category for detailed analysis. This report describes the ice problems at the eight selected sites, focusing on the relationship between channel geometry, hydrometeorological factors, and the historical record of ice events. For each site, tentative structural solutions are proposed.

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Engineering Laboratory

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March 1997

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Division, Research and Engineering Directorate of the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, N.H., and Anthony C. Mamone, an undergraduate student at Dartmouth College, Hanover, N.H., under summer contract to CRREL. The report was technically reviewed by Kevin Carey and Donald Haynes of CRREL.

This study examined confluences with ice problems in the United States. The work, performed under the River Confluence Ice Program, work unit *Structural Ice Mitigation Techniques at Confluences and Mainstems*, followed a comprehensive review of structural ice control methods (Tuthill 1995). The study selected a limited number of representative sites for detailed analysis and development of structural ice control solutions.

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Selection of Confluence Sites with Ice Problems for Structural Solutions

ANDREW M. TUTHILL AND ANTHONY C. MAMONE

INTRODUCTION

Ice jams and ice accumulations on rivers in the United States cause residential flooding, damage river structures, and interfere with winter navigation and hydroelectric production. The formation of an ice jam can block a significant portion of the channel area of a river, forcing the flow out of its banks to flood upstream areas. The release of a jam is similar to a dam break, and the rapidly moving surge of ice and water can threaten downstream property and structures. The economies of many northern towns and cities depend to some extent on winter-long navigation on waterways such as the Mississippi, Illinois, and Ohio Rivers. Heavy ice accumulations on these rivers can delay or suspend winter navigation, placing an economic burden on communities and industry. In addition to ice jam flooding and interference with winter navigation, ice accumulations upstream of hydroelectric facilities can create headlosses that result in decreased electricity production and lost revenues for the utilities.

Many of these ice problems occur at or near confluences. Ice from a tributary creates jams on the mainstem, or an ice accumulation in the mainstem may create a jam at the mouth of the tributary. Jams often form at the slope reduction points, where rivers enter lakes or the pool areas behind dams. Deposition of sediment at these slope-change locations may further reduce the ice conveyance capacity. Ice floes and fragmented lake ice covers also tend to arch and jam at lake outlets. These accumulations can cause undesirable upstream water level increases or release en masse into the river downstream to cause jams. Discharge levels and the timing of ice releases on tributaries and mainstems play important roles, especially on large river systems where individual basins are subject to different weather patterns.

Engineering solutions exist for these ice problems. The ice control methods can be nonstructural or structural. Examples of nonstructural methods include ice breaking and ice cutting, to improve ice passage and reduce the potential for jamming. Explosives and heavy equipment have also been used to remove jams and ice accumulations. Thermal methods have been effective in many applications: the introduction of warm effluent has reduced river ice problems at some sites, and dusting the ice cover with a dark material increases solar heat absorption to weaken and melt the ice cover before breakup occurs. Flow control at dams and river-regulating structures at critical times is also a proven ice control method. USACE (1985) outlines these nonstructural methods.

Because the focus of this work is on structural ice control, we selected confluence ice problem sites favoring structural solutions. Perham (1983), USACE (1985), and Tuthill (1995) describe existing structural ice control methods, including floating ice booms, artificial islands, weirs, and piers. The goal of this study was to select a small number of confluence ice problem sites to represent the spectrum of ice problems encountered in the larger group of sites. A second objective in the selection of sites was to maximize the variety of potential structural solutions and focus on innovative methods.

APPROACH

The preliminary list of possible sites included 40 individual confluences. For each problem site, hydraulic, hydrologic, and meteorological data were collected, along with historic information on ice events, their frequency, and the resulting damages. The sites were categorized into four groupings and ranked according to the criteria of problem magnitude, availability of data, potential for a structural solution, potential for outside collabo-

ration, and potential for a solution by new methods. The highest ranked sites from each group were then selected for analysis of structural ice control alternatives. In addition, sites where successful structural solutions already exist or are currently under development by others were chosen for performance monitoring, since the information gained is of value to the present effort.

Review of the Ice Jam Archive of CRREL's Ice Engineering Research Division (Herrin and Balch 1995) and the Ice Jam Database (White 1996), as well as interviews with personnel in U.S. Army Corps of Engineers districts that deal with ice problems on a regular basis produced the preliminary list of sites presented in Table 1. This list was then divided into four main confluence groups:

1. Confluences of similar sized rivers
2. Confluences of different sized rivers or waterways
3. Rivers entering lakes
4. Lakes entering rivers

Subcategories, based on river size and use, are possible within each of the four main confluence groups.

Within each of the four confluence groups, characteristic traits can be identified. For example, the interaction of regional weather trends, stage and discharge levels, and the timing of ice releases are critical factors for similar sized rivers draining major watersheds. The timing of ice releases is important in different sized river confluences as well. Frazil or floes produced in the smaller stream may enter the mainstem to reduce ice conveyance capacity, or the breakup ice run from a smaller tributary may stall when it encounters the lower water surface slope or the intact ice cover of the mainstem. This problem is also common at river-to-lake confluences. Problems resulting from lake ice entering rivers are less common but can be severe, as in the case of the Lake Erie–Upper Niagara River confluence at Buffalo, N.Y.

INFORMATION SOURCES AND DATA COLLECTED

The amount of available information and data varied greatly with each site. In general, the sites with a high frequency and magnitude of damages tended to have more complete records. Since this examination is preliminary in nature, excessive detail was avoided and the data collection effort focused on information that would aid in the development of structural solutions.

Information and data came from a number of sources, including the collective experience of CRREL Ice Engineering researchers, the Ice Jam Archive, and the Ice Jam Database. Ice Engineering personnel have visited many of the sites in response to ice jam problems or have participated in reconnaissance studies on ice jam flooding. Personnel at Corps districts, particularly St. Louis, Rock Island, Chicago, and St. Paul, provided much additional information.

For each site, we collected sufficient background information to describe the problem, its causes, and its impacts. USGS and National Weather Service records provided the necessary hydrologic, hydraulic, and meteorological data. Hydrologic data included average winter flows and discharges for ice events. Hydraulic data included typical channel depths, widths, slopes, and ranges of current velocities in the confluence areas. Drainage areas were also recorded to give a feel for the overall problem scale and the relative sizes of tributaries and mainstems. Meteorological information included mean monthly temperatures and winter precipitation amounts. Where possible, departures from the mean were noted for periods with ice problems.

The examination of sites included a description of important channel features, river uses, the surrounding environment, and historic ice jam events. The channel was described according to the location of bends, islands, bars, and the natural bed and bank material. The location of dams and other important structures upstream and downstream of the confluence were recorded. Possible river uses include commercial navigation, hydroelectric production, water supply (municipal, commercial, and irrigation), and recreation. In addition, the river or water body's importance in terms of habitat for fish and wildlife was noted. Summaries of historical ice events include dates, peak stages, discharges, damage costs, and frequencies.

SELECTION CRITERIA

The following selection criteria were developed to rank the preliminary list of confluence sites within each of the four main groupings:

Criteria	*Weighting*
Magnitude of the problem	10
Availability of data	5
Potential for a structural solution	10

Table 1. Preliminary list of confluence sites with ice problems.

		Location	*Notes*
Confluences of similar sized rivers			
Kankakee River	Des Plaines River	Dresden Island, Ill.	
Missouri River	Mississippi River	St. Louis, Mo.	
Ohio River	Mississippi River	Cairo, Ill.	
East Branch Ausable River	West Branch Ausable River	Ausable Forks, N.Y.	
Illinois River	Mississippi River	Grafton, Ill.	
West Branch Susquehanna River	East Branch Susquehanna River	Sunbury, Pa.	
Allegheny River	Ohio River	Pittsburgh, Pa.	
Minnesota River	Mississippi River	Minneapolis, Minn.	
Smaller rivers flowing into larger rivers			
Salmon River	Connecticut River	East Haddam, Conn.	
Yellowstone River	Missouri River	Buford, Trenton, N.D.	
Marseilles Lock Canal	Illinois Waterway	Marseilles, Ill.	
Lackawaxen River	Delaware River	Port Jervis, N.Y.	(1)
Israel River	Connecticut River	Lancaster, N.H.	(3)
Oil Creek	Allegheny River	Oil City, Pa.	(2)
Mohawk River	Connecticut River	Colebrook, N.H.	
Allagash River	St. John River	Dickey, Me.	
Rock River	Mississippi River	Rock Island, Ill.	(1)
Elkhorn River	Platte River	Ashland, Neb.	
Loup River	Platte River	Columbus, Neb.	
White River	Connecticut River	White River Junction, Vt.	
Wisconsin River	Mississippi River	Prairie du Chien, Wis.	(1)
Iowa River	Mississippi River	Oakville, Ia.	
South Platte River	North Platte River	North Platte, Neb.	
Fox River	Illinois River	Ottawa, Ill.	(1)
Des Moines River	Mississippi River	Keokuk, Ia.	
Lower Maquoketa River	Mississippi River	Maquoketa, Ia.	
Chena River	Tanana River	Fairbanks, Ak.	
Rivers flowing into lakes or reservoirs			
Aroostook River	Tinker Dam Reservoir	Ft. Fairfield, Me.	
Cazenovia Creek	Lake Erie	Buffalo, N.Y.	(4)
Chagrin River	Lake Erie	Eastlake, Oh.	
Missouri River	Lake Sakakawea	Buford–Trenton, N.D.	
Missouri River	Lake Sharpe	Pierre, S.D.	
Cattaraugus Creek	Lake Erie	Silver Creek, N.Y.	
Deerfield River	Harriman Reservoir	Wilmington, Vt.	
Rocky River	Lake Erie	Cleveland, Oh.	
Vermillion River	Lake Erie	Vermillion, Oh.	
Sandusky River	Lake Erie	Sandusky, Oh.	
Ashtabula River	Lake Erie	Ashtabula, Oh.	
Illinois River	Peoria Lake	Peoria, Ill.	
Oconto River	Lake Michigan	Oconto, Wis.	
East Branch Penobscot	West Branch Penobscot	Medway, Me.	
Cuyahoga River	Lake Erie	Cleveland, Oh.	
Lakes draining into rivers			
Lake Erie	Upper Niagara River	Buffalo, N.Y.	(5)
Lake Huron	St. Clair River	Port Huron, Mich.	

1. Known ice problems on these rivers are not related to the confluence.
2. This problem has been solved by the construction of a weir on Oil Creek and a boom on the Allegheny.
3. No significant ice jam floods have occurred in Lancaster since the construction of the weir in 1984.
4. An ice control weir was designed for this site but never built.
5. Solutions to this problem are currently under investigation by the New York Power Authority.

Potential for collaboration	5
Potential for new methods	10

The five criteria were assigned weightings reflecting the relative importance to the study. The magnitude of the problem, the potential for structural solutions, and the potential for new methods were given priority over the availability of data and the potential for collaboration.

The magnitude of the problem is defined in terms of the total cost of damages and other lost revenue resulting from a confluence ice problem. This assessment is imperfect, since damage estimates are often vague, conflicting, or missing from the record. The availability of data is often linked to problem magnitude because the ice events that cause the greatest damage typically get the most attention.

The third criterion is based on an initial assessment of the feasibility of a structural solution. This criterion may be re-evaluated throughout the course of the project. The development or discovery of new methods may increase the feasibility, but on the other hand, more detailed analysis may find a structural solution less feasible than initially thought.

The fourth criterion addresses the potential for collaboration on structural ice control projects with Corps Districts, state governments, towns, and municipalities. It also assesses the potential for a multifaceted ice control solution. Ice problem sites with the potential of evolving into demonstration projects are favored, since the information gained from field monitoring of a structure's performance is extremely valuable. A multifaceted approach is valuable because, in the past, some of the most successful ice management programs have combined structural methods with other forms of ice control such as prediction, surveillance, thermal or mechanical ice weakening, flow control, or channel modification.

The fifth criterion was included to encourage the development of new methods. An ice problem that has traditionally been thought impossible or too expensive to solve by existing structural means might yield to a new approach.

RANKING AND SELECTION OF SITES

For each of the four confluence groupings, the sites were ranked according to the weighted criteria that translated qualitative judgment into a quantitative format. How well a site met an individual criterion was assessed on a scale from 1 to 10. This score was then multiplied by the weighting factor for that criterion to produce a weighted score. The sum of the weighted scores was divided by the sum of the five individual weighting factors, to produce a final score for each site. Several sites were then selected from the top of each list for development of structural solutions. It was important to determine whether the problem is actually related to *confluence* ice processes. For example, recurrent ice jamming in a tributary as a result of backwater on the mainstem is a common ice problem related to river confluences. Another example is an ice blockage of the mainstem resulting from a large ice release from the tributary. In some cases, the initial examination of sites revealed that the confluence itself played little or no role in the local ice problem. These sites were dropped from the final list.

Confluences of similar sized rivers

Confluences of similar sized rivers appear with their rankings in Table 2. The first site selected is the Kankakee–Des Plaines confluence (to form the Illinois River). The second site, the middle Mississippi River, extends from the Missouri River confluence to the Ohio River confluence. The ice problems at these two locations are summarized below.

Kankakee River–Des Plaines River confluence

The Kankakee River joins the Des Plaines River 1.5 miles upstream of the U.S. Army Corps of Engineers Dresden Island Lock and Dam on the Illinois River (Fig. 1). Thick frazil deposits on two steep reaches of the lower Kankakee supply ice to destructive breakup jams that periodically flood housing developments downstream near the Will–Grundy county line. The frazil accumulations can progress upstream as far as Wilmington, Illinois. In years when this occurs, the breakup ice run may jam against these frazil deposits to flood parts of the community. During the 52-year period from 1935 to 1986, there were 26 ice jam floods in the Will–Grundy county line area and/or upstream in Wilmington. The most costly event occurred in 1982, with damages estimated at $8.2 million. In 1985, the release of a breakup jam on the lower Kankakee severely damaged two of the tainter gates at the Dresden Island Dam.

The problem has been somewhat reduced since the construction in 1988 of a siphon to pull water from the cooling pond of the Dresden Island Nuclear Power Plant into the river. This warmer

Table 2. Confluences of similar sized rivers, ranked according to selection criteria.

Tributary	*Mainstem*	*Location*	*Magnitude of problem* 10	*Availability of data* 5	*Potential for structural solution* 10	*Potential for collaboration* 5	*Potential for new methods* 10	*Weighted average*
Kankakee River	Des Plaines River	Dresden Island, Ill.	10	10	10	10	7	9.3
Missouri River	Mississippi River	St. Louis, Mo.	10	10	5	10	10	8.8
Ohio River	Mississippi River	Cairo, Ill.	10	8	4	8	7	7.3
East Branch Ausable River	West Branch Ausable River	Ausable Forks, N.Y.	6	5	7	3	7	6.0
Illinois River	Mississippi River	Grafton, Ill.	4	5	10	5	1	5.0
West Branch Susquehanna River	East Branch Susquehanna River	Sunbury, Pa.	1	1	0	0	0	0.4
Allegheny River	Ohio River	Pittsburgh, Pa.	1	1	0	0	0	0.4
Minnesota River	Mississippi River	Minneapolis, Minn.*	?	1	0	0	0	0.1

*Known ice problems on these rivers are not related to the confluence.

water melts frazil ice at the downstream end of the lower of the two steep reaches shown in Figure 1. The siphon was recommended by a Section 205 Reconnaissance Study on ice jam flooding (USACE 1990) done by the Chicago District. The study also recommended the installation of an ice boom upstream of the dam at Wilmington and the addition of flashboards along the spillway crest. The boom would help form an early-season ice cover, reducing the volume of frazil in the steep reach downstream of town. Preventing the freezeup ice accumulation from progressing as far upstream as Wilmington would reduce the threat of ice jam flooding at the time of breakup. The flashboards would raise the water surface elevation by 1 ft and lengthen the pool. This should improve ice boom performance, particularly during periods when above-average discharge and extremely cold air temperature coincide. Although there are a preliminary design and cost estimate

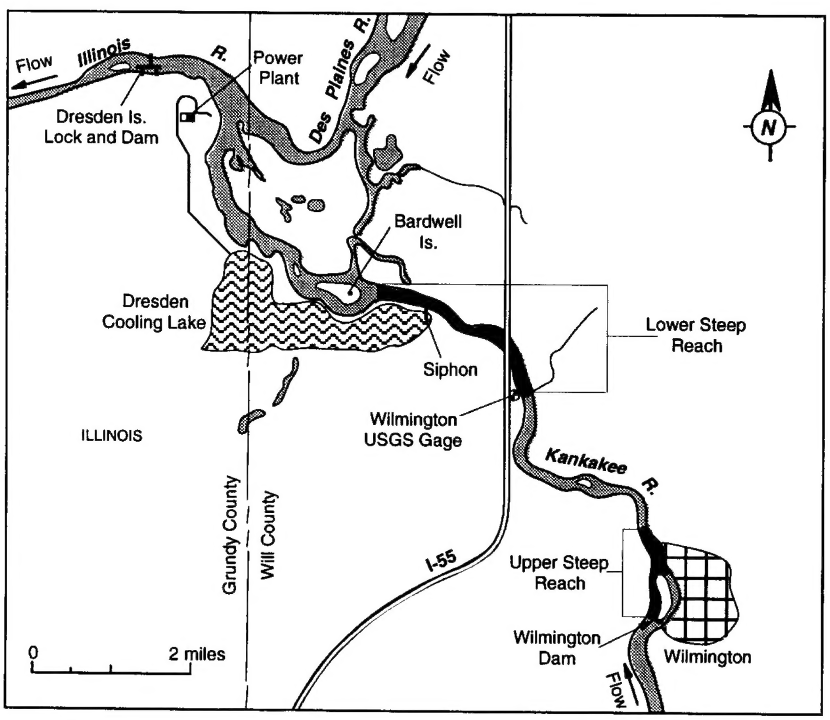

Figure 1. The Kankakee River—Des Plaines River confluence area.

for the ice retention alternative (USACE 1990), the project has not gone ahead to date.

The Kankakee River, with a total drainage area of 5,208 mi^2, has a mean annual discharge of 4,262 ft^3/s at the Wilmington gage, and an average flow of 4,700 ft^3/s for the December through February period. The Kankakee is a pool-riffle, rock-bedded river with an overall slope of 0.0004, increasing to 0.002 in the steeper reaches. Channel width ranges from 300 to 700 ft. The Des Plaines River, with a mean annual discharge of 8,990 ft^3/s, is relatively flat and forms part of the Illinois Waterway, which is open to navigation throughout the winter. The Dresden Island Dam, located 1.5 miles downstream of the confluence, on the Illinois River, extends its pool to river mile 3.5 on the Kankakee. The slope reduction and the intact ice cover on the Dresden Island pool combine to stall the breakup ice run on the Kankakee, creating the ice jam problem in the Will–Grundy county line area.

The coldest month of the year is January, with a long-term average temperature of 33.3°F. Severe ice events are typically preceded by 3- to 4-week-long periods with the average temperature in the 20–25°F range. Rapid thaw with rainfall typically triggers midwinter breakup ice events.

This site merits consideration for many reasons. As indicated by the recommendations of the Section 205 study, there is high potential for a successful structural solution to reduce the frazil production on the lower Kankakee. Data and information are readily available, and a spirit of cooperation exists between CRREL's Ice Engineering Research group, the Chicago District of the Corps, and the State of Illinois. The study has the potential for progressing into a demonstration ice control project. At present, Ice Engineering Research has provided the Chicago District with an ice-hydraulic analysis of the lower Kankakee River and a preliminary ice boom design.

Missouri River–middle Mississippi River–Ohio River

Periods of severe cold in the Midwest can cause ice covers and freezeup ice jams to form on the middle Mississippi River, stretching 195 miles from the Ohio River confluence near Cairo, Illinois, to the confluence with the Missouri River, upstream of St. Louis (see Fig. 2). The Missouri River, uncontrolled for 800 miles upstream of its confluence with the Mississippi, is a major source of frazil ice. In addition, a significant portion of the ice originates in the undammed middle Mississippi itself. Low-flow periods combined with severe cold can result in ice blockage of the Mississippi at its confluence with the Missouri. Once the blockage is formed, rain or warming can cause the ice cover or "ice fields" on the middle Mississippi to collapse and thicken into a jam or "gorge." At times, these jams can be as thick as 20 ft and resist all efforts to re-open the navigation channel by ice breaking. In the past, ice cover has caused the suspension of winter navigation for periods of weeks. In the worst cases, breakup of the ice cover occurs as a series of ice runs and jams, resulting in serious damage or destruction of structures and/or barges and tows remaining in the system.

Bad ice years occur roughly one year in ten, with 1989, 1979, 1977, 1962, 1958, 1951, and 1936 standing out in the recent historical record. The winter of 1977 was the worst of these cases. Nine hundred barges were delayed at Cairo for 27 days at an estimated cost of $19 million. In addition, river regulating structures below Commerce, Missouri,

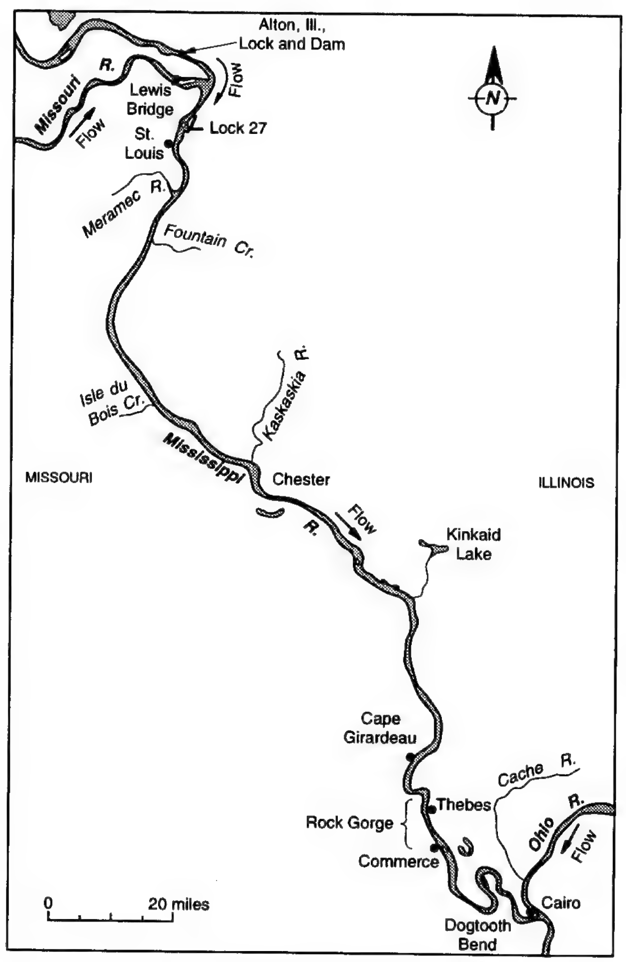

Figure 2. Map of middle Mississippi River, St. Louis, Missouri, to Cairo, Illinois.

incurred substantial damage when the ice released. Even during winters without major ice events, delays to navigation and operational difficulty resulting from ice are common problems.

A number of studies have been done on middle Mississippi ice problems by the St. Louis District (USACE 1962, 1977). The ice problems of 1962 prompted the District to put together a predictive model for ice jams based on detailed historical records of flow, stage, water, and air temperature as well as ice conditions. The 1977 ice season prompted a physical model study of a generic reach, done by researchers at the University of Missouri–Rolla (Stevens 1978). The study covered arching and ice cover initiation, the effects of flow control, and ice forces on dikes. Recommendations included booms to stabilize the ice cover and the use of scheduled tow and barge passages to continually flush ice through jamming-prone reaches. The study concluded that ice jam prevention was the only feasible solution. The scale of the problem makes breaking existing jams difficult to impossible. Flow manipulation was deemed unfeasible because of the risk that fluctuations in discharge could cause the ice cover to collapse and thicken into a more serious jam.

The Mississippi River at St. Louis has a mean annual discharge of 187,000 ft^3/s, draining 697,000 mi^2. The Missouri River, having a drainage area of 420,000 mi^2 at St. Joseph, Missouri, near its mouth, contributes 42,000 ft^3/s of this flow. Near its confluence with the Mississippi, the Ohio River drains 203,000 mi^2 with a mean annual discharge of 273,000 ft^3/s. For the months of December through February, long-term average discharge in the middle Mississippi at St. Louis is 127,000 ft^3/s. For years with ice problems, average winter flow is substantially lower, in the 50,000 to 95,000 ft^3/s range. In addition to lower flow, average temperatures for the months of December and January are roughly 10°F below the long-term average of 33°F during winters with severe ice problems (Lovelace et al. 1981) (see Appendix A).

The middle Mississippi can be divided into three geomorphologic reaches. Below St. Louis, the river follows a 4- to 5-mile-wide alluvial valley with a slope of 0.0001 for a distance of 134 miles. From a point about 4 miles below Cape Girardeau to Commerce, Missouri, the river follows a half- to three-quarter-mile-wide rock gorge for 7 miles. The gorge is a common jamming location during severe ice years. For the remaining 40 river miles, from Commerce to the Ohio confluence, the Mississippi follows a wide delta-like valley with a channel width of roughly 1 mile. Ice accumulates at both the confluence and the Dogtooth Bend area 12–24 miles upstream. There are many dikes, revetments, and levees within this reach that sustain infrequent but severe ice damage. Water current velocities can be as high as 5 to 6 ft/s, and major stage fluctuations are possible in both the middle Mississippi and the Missouri Rivers. Bed and bank material ranges from rock ledge to fine silts.

Structures upstream of St. Louis provide a high level of ice control. The system of 25 locks and dams on the upper Mississippi, extending as far north as St. Paul, Minnesota, effectively prevents all but minor ice quantities from entering the middle Mississippi. Similar structures on the Illinois River prevent that tributary's ice from contributing significantly to ice problems on the middle Mississippi. Many of the dams produce hydroelectric power. The upper Mississippi is closed to navigation from 1 December to 1 April each year above Lock and Dam 20 at Canton, Missouri. The most downstream dam on the Missouri River is 800 miles above the mouth at Gavins Point, near Yankton, South Dakota. The river is closed to winter navigation. In addition to their commercial uses, both the middle Mississippi and the Missouri provide important habitat for fish and wildlife.

For a problem of this scale, any solution would need to be multifaceted. Booms could promote ice cover growth and stabilize the ice cover in lower-velocity reaches. Structural methods to retain Missouri River ice until the middle Mississippi is ice-free need to be investigated. Any such structures would need to be removable to avoid hazards to regular season navigation. Flow control on the Ohio could possibly reduce the backwater on the Mississippi above Cairo, but reservoir storage volume requirements would take precedence. Ice breaking and ice flushing in problem reaches merit further examination. All of these schemes would rely on the prediction of ice problems and close surveillance of the river and its tributaries during the ice season.

The middle Mississippi is an excellent site for the development of structural ice control schemes. Two major river confluences are involved. The Missouri acts as an ice source, and the Ohio River creates a backwater condition, affecting, to some degree, ice cover and ice jam formation. The scale of the problem and the resulting damages are great. Winter-long navigation as well as damage to structures and shipping are important economic issues. Data on past events are available, and the

potential for pre-existing or new structural solutions exists.

Confluences of smaller into larger rivers

Confluences of smaller into larger rivers are ranked in Table 3. Selected for detailed analysis are the Salmon River–Connecticut River confluence at East Haddam, Connecticut, the Yellowstone River–Missouri River confluence near Buford, North Dakota, and the Illinois Waterway confluence with the Marseilles Lock. The Oil Creek–Allegheny River and Israel River–Connecticut River confluence ice problems have been significantly reduced by the construction of ice control structures, and their performance will continue to be monitored.

Salmon River–Connecticut River

The Salmon River is a steep, frazil-producing tributary of the tidal portion of the Connecticut River (Fig. 3) (see Appendix A). Much of the 111-mi^2 catchment of the Salmon River is underlain by relatively impermeable glacial till. The intense rainfall produced by winter storms on the Atlantic creates a rapid runoff response that can result in extremely dynamic breakups. High winds during these storms can produce abnormally high tides that raise the level of the Connecticut backwater, further compounding the ice jam flood problem.

During 1979 and 1980, the decaying 22-ft-high Leesville Dam, upstream of the settled area, was lowered by 10 ft for safety reasons and for the construction of a fish ladder to encourage the return of Atlantic salmon. The reduction in height allowed the breakup ice run to pass over the spillway and jam in the bridge opening of the Highway 151 embankment 1,500 ft downstream. Such an event occurred on 1 Feb 1982. On 29 Jan 1994, the ice run proceeded 500 ft beyond the Route 151 bridge, to stop against the intact downstream ice cover. Both events caused flooding and ice damage to residential property.

Upstream of the Leesville Dam pool, the Salmon River has a steep average slope of 0.004. Channel width ranges from 75 to 150 ft. Depths are typically in the 2- to 6-ft range, and water velocity 3 to 4 ft/s. The average winter base flow ranges from 50 to 200 ft^3/s, and a 1-ft-thick ice cover breaks up and moves at or above a discharge of approxi-

Table 3. Confluences of smaller to larger rivers, ranked according to selection criteria.

Tributary	*Mainstem*	*Location*	*Magnitude of problem 10*	*Availability of data 5*	*Potential for structural solution 10*	*Potential for collaboration 5*	*Potential for new methods 10*	*Weighted average*
Salmon River	Connecticut River	East Haddam, Conn.	4	8	9	9	9	7.6
Yellowstone River	Missouri River	Buford, N.D.	7	9	7	9	6	7.3
Marseilles Lock Canal	Illinois Waterway	Marseilles, Ill.	6	5	8	7	8	7.0
Lackawaxen River	Delaware River	Port Jervis, N.Y. (1)	5	7	8	7	8	7.0
Israel River	Connecticut River	Lancaster, N.H. (3)	6	8	9	6	6	7.0
Oil Creek	Allegheny River	Oil City, Pa. (2)	9	9	9	9	0	6.8
Mohawk River	Connecticut River	Colebrook, N.H.	3	5	9	2	6	5.4
Allagash River	St. John River	Dickey, Me.	4	7	6	5	5	5.3
Rock River	Mississippi River	Rock Island, Ill. (1)	2	8	8	8	1	4.8
Elkhorn River	Platte River	Ashland, Neb.	7	6	2	7	3	4.6
Loup River	Platte River	Columbus, Neb.	7	6	2	7	3	4.6
White River	Connecticut River	White River Jct., Vt.	4	8	3	4	3	4.0
Wisconsin River	Mississippi River	Prairie du Chien, Wis. (1)	?	5	10	5	1	4.0
Iowa River	Mississippi River	Oakville, Ia.	5	3	1	2	1	2.4
South Platte River	North Platte River	North Platte, Neb.	?	2	1	2	1	1.0
Fox River	Illinois River	Ottawa, Ill. (1)	1	1	0	0	0	0.4
Des Moines River	Mississippi River	Keokuk, Ia.	?	1	0	0	0	0.1
Lower Maquoketa River	Mississippi River	Maquoketa, Ia.	?	1	0	0	0	0.1

1. Known ice problems on these rivers are not related to the confluence.
2. This problem has been solved by the construction of a weir on Oil Creek and a boom on the Allegheny.
3. No significant ice jam floods have occurred in Lancaster since the construction of an ice control weir in 1984.

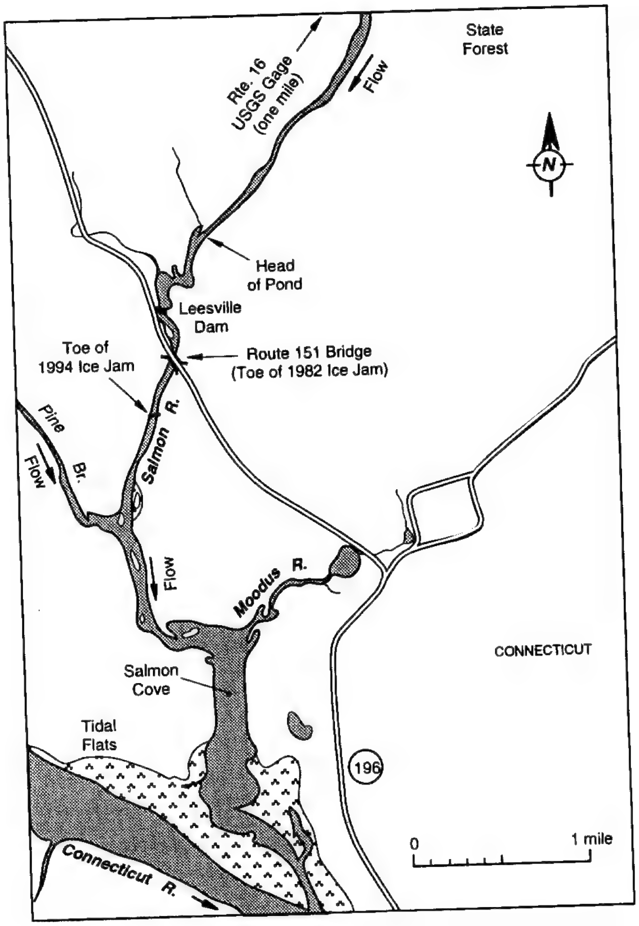

Figure 3. The Salmon River–Connecticut River confluence area, East Haddam, Connecticut.

mately 1,000 ft^3/s. The river bed is predominantly sand and gravel, derived from the underlying till, and large quantities of this bed material move downstream during high-flow events. The 3.5-mile-long reach above the Leesville Dam lies within a state forest, providing recreation and habitat for fish and wildlife.

The Salmon River–Connecticut River confluence merits detailed analysis for a number of reasons. The site is representative of the trend toward increased ice problems in small communities as old mill dams decay or are removed. The river hosts recreation and an Atlantic salmon run, so any structural solution would have to be sensitive to environmental issues. The CRREL Ice Engineering Research Division has followed the problem for over a decade, and there is a solid base of historic information and data. The New England Division of the Corps of Engineers (NED), at the request of the State of Connecticut Department of Environmental Protection (CT-DEP), funded a Section 22 study to develop a structural solution to the ice jam flood problem at Leesville. Under the study, Ice Engineering researchers developed a preliminary design for an ice control structure to be located above the Leesville Dam (Tuthill et al. 1995). The study has potential for progressing into a demonstration project.

Yellowstone River–Missouri River

Since the closure of Garrison Dam and the filling of Lake Sakakawea in 1953, the combination of raised groundwater levels and channel bed aggradation at the head of the reservoir have resulted in an increased incidence of ice jam flooding in the Buford–Trenton Irrigation District (see Fig. 4). The Yellowstone River typically breaks up and runs several weeks before the mainstem Missouri River does. The breakup progresses in a series of jams and releases down the Yellowstone, passing through the confluence area and then proceeding down the Missouri toward the headwaters of Lake Sakakawea. Six incidents of ice jam flooding occurred between 1952 and 1990. Since the land in the Buford–Trenton Irrigation District is extremely flat, the overtopping of levees or laterals results in the flooding of large tracts of agricultural land and the evacuation of farms. Channel bed aggradation at the head of Lake Sakakawea continues at an estimated rate of 1 ft every 6–7 years, further decreasing the ice conveyance capacity.

The Missouri River at Williston, North Dakota, has a drainage area of 164,500 mi^2 with a mean annual discharge of 20,405 ft^3/s. Average discharge for the December through February period on the Missouri is 10,500 ft^3/s (see Appendix A). Breakup discharge is estimated at 25,000 ft^3/s (Wuebben et al. 1995). Channel width varies from 500 to 1000 ft, and thalweg depth ranges from 10 to 20 ft. Water current velocity runs between 1 and 3 ft/s, and water surface slope is between 0.0001 and 0.0002. The lower Yellowstone River is similar in slope and enters the Missouri River 22 miles upstream of Williston. It drains 70,000 mi^2. Within the area of interest, both the Missouri and the Yellowstone have moveable beds, composed of material in the fine silt to sand size range. Garrison Dam lies 170 miles downstream of the confluence, and Fort Peck Dam is located on the Missouri, 200 miles upstream of the Yellowstone confluence.

The reservoirs on the upper Missouri store water principally for irrigation. The Garrison and Fort Peck Dams also produce hydroelectric power. Both

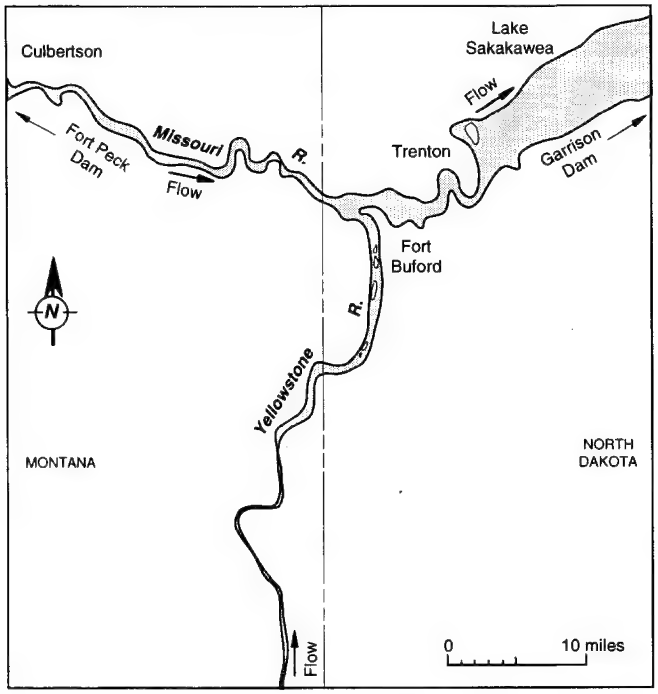

Figure 4. The Yellowstone River–Missouri River confluence area near Buford, North Dakota.

the Yellowstone and the Missouri provide important habitat for fish and wildlife.

Ice jam problems at the Yellowstone–Missouri confluence are correlated with extremely cold air temperatures and deep snow cover. The coldest month of the year is January, with an average air temperature of only 19°F. From 1952 to 1992, the average of the maximum accumulated freezing degree days at Williston, N.D., was 2012°F. The average for the six winters with known ice jams (1952, 1972, 1975, 1976, 1978, and 1986) was somewhat higher at 2325°F.* Depth of snow on the ground at the time of breakup appears to be related to ice problems as well. The average snow depth was 31 inches for the six winters with known ice jams. For non-ice jam years, the average depth of snow on the ground at the time of breakup was 26 inches. Wuebben et al. (1992) theorize that the thicker snow cover insulates the ice from solar radiation, delaying its deterioration and increasing the ice jam potential.

This site has high potential for a structural solution. The ice jam flood threat in the Buford–Trenton Irrigation District could be reduced substantially by retaining the Yellowstone ice run until the Missouri River is ice free from the confluence downstream into Lake Sakakawea. Since the ice tends to jam there naturally, a likely site for an ice retention structure is on the Yellowstone immediately upstream of the confluence. Wuebben et al. (1992) list rock-filled timber cribs, spur dikes, and ice control weirs as potential structural ice retention measures at this location. Retention of Yellowstone ice could be done in conjunction with dusting along the Missouri to speed the deterioration of the mainstem ice.

Since the ice jam flood problem in the vicinity of Williston, N.D., was the subject of a recent study (Wuebben et al. 1995), information and data are readily available.

Marseilles Lock–Illinois Waterway

The U.S. Army Corps of Engineers Marseilles Lock is plagued annually by ice problems at both its upstream and downstream approaches. Upstream of the lock, brash ice that fills the 2.7-mile-long × 350-ft-wide slackwater approach channel is pushed into the lock by arriving tows (see Fig. 5). During heavy ice periods, as many as three ice

*Accumulated freezing degree days in °F is defined by: $\mathrm{AFDD} = \sum_{i=1}^{n}(T_o - T_i)$, where n = number of consecutive days; T_o = 32°F; T_i = daily average air temperature on day i in °F. Ice thickness can be related to AFDD by $T_{ice} = \mathrm{K}\sqrt{\mathrm{AFDD}}$, where T_{ice} = ice thickness in inches. The constant K typically ranges from 0.4 to 0.8.

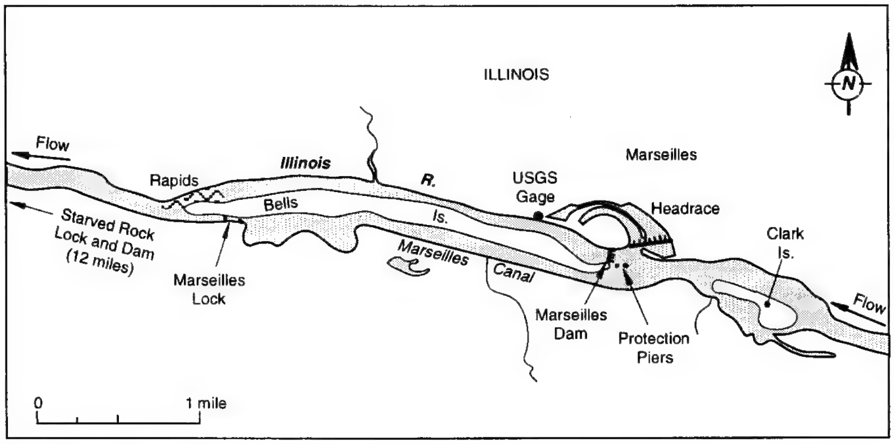

Figure 5. Map of Marseilles Lock and Dam on the Illinois Waterway at Marseilles, Illinois.

lockages may be needed to pass a single tow. The canal and lock bypass a steep reach that remains open throughout the winter, producing large volumes of frazil. Near the downstream entrance of the Marseilles Lock, the frazil created in the steep reach jams against the upper end of the sheet ice covering the pool of the Starved Rock Lock and Dam, located 13 miles downstream. A half-mile-long by 6- to 7-ft-thick jam forms nearly every winter, interfering with tow and barge traffic operating on the waterway.

The approach canal to the Marseilles Lock carries only enough discharge for lockages, so its ice conveyance capacity is minimal. The Marseilles Dam is located at the upstream end of the canal (see Fig. 5). A narrow island separates the canal from the mainstem of the river, which is 650 ft wide with an average slope of 0.0007. Moving upstream from the head of the Starved Rock pool toward the Marseilles Dam, the average depth decreases from 8 to 1 ft and average water current velocity increases from 2.5 to 4.0 ft/s. The drainage area for the Illinois River at this site is 8,259 mi^2, and the average flow for the December through February period is approximately 10,500 ft^3/s (see Appendix A).

In addition to year-round commercial navigation, the Illinois Waterway is used by recreational boaters and fishermen. It provides water to communities and industry, and some of the dams produce a limited amount of hydroelectric power.

Although there are no drastic ice-related damages, the ice problem at the Marseilles Lock manifests itself every winter in the form of increased operational costs to the Corps and financial losses to navigation because of delays. Operations at the Rock Island District believe that Marseilles Lock has the one of the worst ice problems in the District.*

The Marseilles Lock ice problem was studied under the River Ice Management (RIM) Program, and a variety of structural solutions were proposed (Foltyn 1985). Among the options considered were fence booms and submarine nets to promote the growth of a frazil dam that would create a stepped ice cover upstream of the traditional jam area. The construction of a series of small weirs and installation of an inflatable fabric dam were also considered. The 1985 study did not address the ice problem at the upstream entrance to the lock. A potential solution might be the construction of an ice chute across the island to convey brash ice away from the lock entrance. In addition, a shear boom could be designed to reduce the amount of ice entering the approach canal's upstream end, but ice formed within the canal itself could still pose problems.

There is a moderate amount of data and information available on the Marseilles Lock ice problem. The Marseilles site differs from others because it is closely related to the issues of winter navigation and lock operations. Although no steps have been taken at this point, there is potential for collaboration with the Rock Island District, particularly with personnel in Operations.

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*William Gretten, Operations, Rock Island District, USA Corps of Engineers, April 1994, personal communication.

Confluences of rivers into lakes

Confluences of rivers into lakes or reservoirs are ranked in Table 4. This study selected for detailed analysis the Aroostook River–Tinker Dam Reservoir confluence near Fort Fairfield, Maine, and the Chagrin River–Lake Erie confluence at Eastlake, Ohio. The Cazenovia Creek–Lake Erie confluence site was not selected because the ice problem there has been thoroughly investigated in past studies, and plans exist for an ice control weir

Aroostook River–Tinker Dam Reservoir, near Fort Fairfield, Me.

Breakup ice jams frequently form in the Aroostook River downstream from Fort Fairfield, Maine. Although breakup is possible any time during the winter, the most destructive jams occur in late winter or early spring. The breakup proceeds downstream as a series of jams and releases, until finally coming to rest at the Tinker Dam pool. Fifteen damaging breakup ice jams have occurred on the Aroostook River in the past 72 years. The flood of record in Fort Fairfield occurred on 16 April 1994. The peak stage for that event was nearly 4 ft higher than the second highest stage, which resulted from an ice jam in April of 1991. The devastation of 16 April 1994 resulted from a massive surge of ice and water from upstream that ran into a substantial jam already in place. The estimated damages of $5 million resulted from ice impact as well as from flood water. Ice supplying the second jam was observed passing over the Caribou Dam, 12 miles upstream of Fort Fairfield (see Fig. 6). On release, the Fort Fairfield ice accumulation passed over Tinker Dam. Near the dam, two Canadian border guards lost their lives when their vehicle was overwhelmed by the surge of ice and water.

The Aroostook River flows in a northeasterly direction toward its confluence with the St. John River, about 7 miles downstream of Fort Fairfield. The river drains 2,370 mi^2. The average slope is 0.0007, and winter base discharge is approximately 1,000 ft^3/s (see Appendix A). Breakup discharge ranges from 10,000 ft^3/s to instantaneous values in excess of 40,000 ft^3/s.

Below Fort Fairfield, at the upstream end of the Tinker Dam pool, are sand bars and islands that could have a role in ice jam initiation. In addition to the jam at the Tinker Dam pool, temporary jams occur at several upstream locations between Caribou and Fort Fairfield. Between the two towns, both sides of the river are lined with roads, isolated houses, and a railroad. The banks are fairly stable and the predominant bed material is sand. The Tinker Dam, located in New Brunswick, Canada, 4 miles downstream from Fort Fairfield, has a hydroelectric generating capacity of 11,500 kW. In 1965, the construction of two 9.5-ft-high

Table 4. Confluences of rivers entering lakes or reservoirs, ranked according to selection criteria.

Tributary	*Mainstem*	*Location*	*Magnitude of problem* 10	*Availability of data* 5	*Potential for structural solution* 10	*Potential for collaboration* 5	*Potential for new methods* 10	*Weighted average*
Aroostook River	Tinker Dam Pool	Ft. Fairfield, Me.	9	8	6	9	8	7.9
Cazenovia Creek	Lake Erie	Buffalo, N.Y.	7	8	9	6	8	7.8
Chagrin River	Lake Erie	Eastlake, Oh.	6	5	8	7	7	6.8
Missouri River	Lake Sakakawea	Buford, N.D.	7	8	5	6	7	6.5
Missouri River	Lake Sharpe	Pierre, N.D.	7	9	5	5	7	6.5
Cattaraugus Creek	Lake Erie	Silver Creek, N.Y.	6	5	7	5	6	6.0
Deerfield River	Harriman Reservoir	Wilmington , Vt.	5	3	6	3	7	5.3
Rocky River	Lake Erie	Cleveland, Oh.	6	4	6	2	5	5.0
Vermillion River	Lake Erie	Vermillion, Oh.	6	5	5	2	5	4.9
Sandusky River	Lake Erie	Sandusky, Oh.	4	2	5	2	5	4.0
Ashtabula River	Lake Erie	Ashtabula, Oh.	5	7	2	4	3	3.9
Illinois River	Peoria Lake	Peoria, Ill.	3	3	4	3	5	3.8
Oconto River	Lake Michigan	Oconto, Wis.	5	4	1	4	3	3.3
East Branch Penobscot	West Branch Penobscot	Medway, Me.	2	3	4	1	4	3.0
Cuyahoga River	Lake Erie	Cleveland, Oh.	?	1	0	0	0	0.1

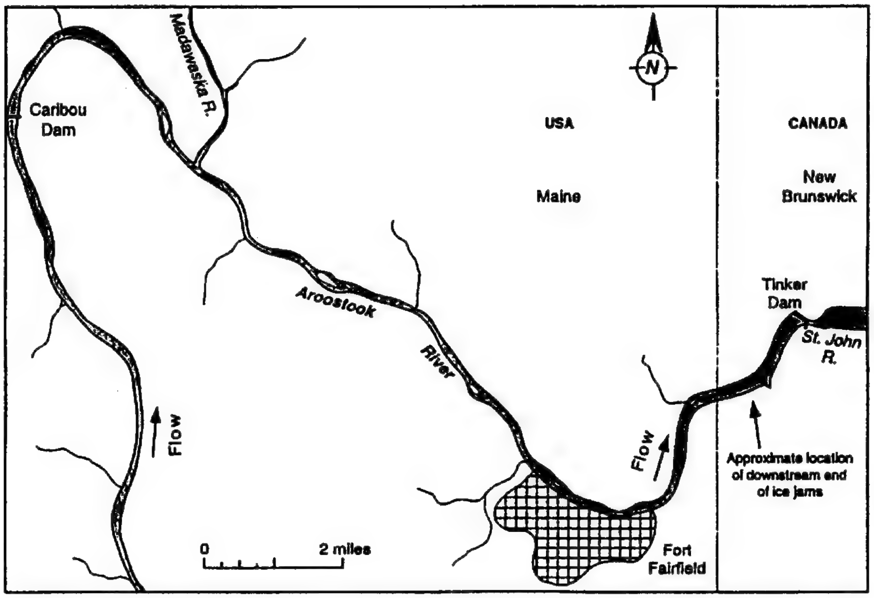

Figure 6. The Aroostook River–Tinker Dam confluence at Fort Fairfield, Maine.

bascule gates raised the normal pool from 347 to its present level of 352 ft above sea level.

The ice jam problem on the Aroostook River has been the subject of two recent studies involving the Ice Engineering Branch. Wuebben et al. (1995) estimate ice jam water surface profiles for various ice retention alternatives upstream of Fort Fairfield, concluding that ice retention structures would be needed at several locations upstream of the town. A second study (White and Acone 1995) examined the effect of the operation of Tinker Dam on the upstream ice conditions at Fort Fairfield. In addition, Ice Engineering researchers are currently monitoring the success of an ice breaking effort, which began in 1995, below Fort Fairfield. Between Ice Engineering's involvement and the records of Maine Public Service Company (the operator of the Tinker Dam), much data and information are available on ice problems at Fort Fairfield.

There is potential for structural ice control between Caribou and Fort Fairfield. Any plan to retain the breakup ice run would need to consider carefully upstream effects on water levels. The 1994 breakup event clearly shows that any ice control structure on the Aroostook needs to withstand high force levels and be capable of storing a large volume of ice. It is unlikely that a plan to retain ice structurally above Fort Fairfield would evolve into a demonstration project in the near future. However, the site is worth detailed examination since the ice jam flood threat is so great and no clear solutions by other means exist at this time.

Chagrin River into Lake Erie at Eastlake, Ohio

Breakups on the Chagrin River have resulted in severe ice jam flooding at the confluence with Lake Erie in Eastlake, Ohio, and 12 miles upstream in the community of Willoughby Hills (see Fig. 7). The ice problems on the Chagrin River are representative of many other confluences of small, northerly flowing rivers with Lake Erie. Among them are Cazenovia Creek at West Seneca, N.Y., Cattaraugus Creek at Silver Creek, N.Y., and the Vermillion River at Vermillion, Ohio. The events occur in mid- to late winter and are triggered by significant rainfall. The river breaks up in sections, with the ice moving downstream in a series of jams and releases. In the Willoughby Hills area, the jams tend to form at bridge openings and bends, and most of the residential developments near the river are vulnerable to the resulting ice jam flooding and ice impact. On the lower Chagrin River, the combination of the Lake Erie backwater, bends in the river, and siltation from the lake stops the breakup ice run and causes flooding of neighborhoods in Eastlake. The flood events in Willoughby Hills and Eastlake can occur simultaneously because each problem area has its own ice supply.

The Chagrin River has experienced 18 ice jam floods since 1913; the most severe occurred in the winters of 1959, 1978, and 1994. For both of the

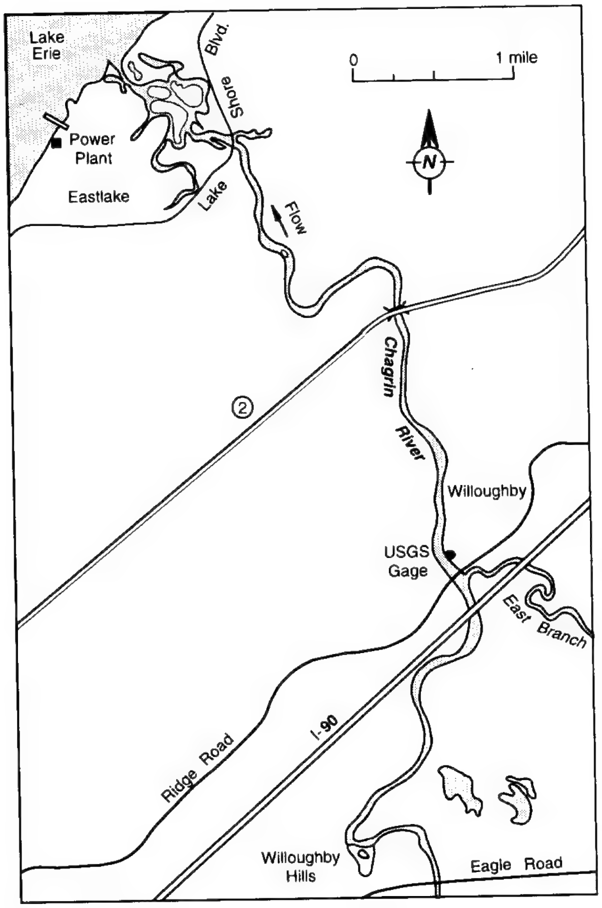

Figure 7. The Chagrin River–Lake Erie confluence area, Eastlake and Willoughby Hills, Ohio.

two most recent events, the damages were estimated at about $1 million. The ice jam flood of January 1959 caused the evacuation of 300 homes and five deaths when a rescue boat capsized. The jam then froze in place and caused a second ice jam flood during the March breakup.

The Chagrin River watershed has an area of 268 mi^2, with an average channel slope of 0.0013. Meanders are common in the lowermost 12 miles, from Willoughby Hills to Eastlake, and the backwater from Lake Erie extends roughly 1 mile upstream from the mouth. Average winter base flow is 190 ft^3/s, and breakup discharges range from 6,000 to 22,000 ft^3/s (see Appendix A). There is significant residential development on the floodplain, both in Willoughby Hills and in Eastlake. The lower Chagrin River also provides access to Lake Erie for many recreational boaters.

This is a favorable site for detailed examination. Information and data on the ice problems on the Chagrin River are readily available, and researchers from the Ice Engineering Division have visited the site on several occasions. A November 1989 memorandum from Ice Engineering to the Buffalo District of the U.S. Army Corps of Engineers recommended the option of retaining breakup ice at a location 4.5 miles upstream of the mouth. Other options included the diversion of warm water from a power plant on the shore of Lake Erie to melt river ice and dredging to improve ice conveyance and provide flow relief. The Buffalo District produced a report on the flood of 14–16 March 1978 (USACE 1978) containing much background information. It is likely that the Buffalo District and local interests would be receptive to any ice control alternatives aimed at reducing the ice jam threat at Eastlake and Willoughby Hills.

Lake–river confluences

The two sites in the lake–river group of confluences are ranked in Table 5. Structural solutions for preventing wind-driven lake ice from entering the Upper Niagara River at Buffalo, N.Y., are being researched by the New York Power Authority (NYPA) and Fleet Technology, Inc. Their progress will be followed. The other site, the confluence of Lake Huron and the St. Clair River, has been selected for detailed analysis and is described below.

Confluence of Lake Huron and the St. Clair River

The St. Clair River forms the natural outlet for the upper Great Lakes (Lakes Superior, Michigan, and Huron). Lake ice entering the St. Clair River can cause substantial jams that may directly affect long-term water levels on Lakes Huron and Michigan (Daly 1992). The jams also flood residential areas and disrupt commercial navigation. With the onset of subfreezing weather, ice accumulates in southern Lake Huron, typically forming an ice bridge across the head of the St. Clair River. This natural arch remains intact most of the winter, keeping the river downstream relatively ice-free until the spring breakup. Wind-driven storms periodically break up the ice bridge, however, allowing floes to move rapidly to the lower river, where they tend to jam just above the delta. The jam then progresses upstream (see Fig. 8). The ice event of record that occurred in April of 1984 affected water levels and discharges throughout the Great Lakes system and suspended navigation between Lakes Huron and Erie. The river was officially closed for 24 days at an estimated loss to commercial shipping of $40 million (Derecki and Quinn 1986).

Table 5. Confluences of lakes entering rivers, ranked according to selection criteria.

Tributary	*Mainstem*	*Location*	*Magnitude of problem* 10	*Availability of data* 5	*Potential for structural solution* 10	*Potential for collaboration* 5	*Potential for new methods* 10	*Weighted average*
Lake Erie	Upper Niagara River	Buffalo, N.Y.*	10	10	7	6	9	8.5
Lake Huron	St. Clair River	Port Huron, Mich.	8	7	7	5	7	7.0

*Solutions to this problem are currently being investigated by the New York Power Authority and Fleet Technology, Inc.

The St. Clair River, with a drainage area of 222,400 mi^2, is the natural outlet for the upper Great Lakes. The combined water surface area of these lakes is 77,000 mi^2. The average annual surface ice discharge (December–April) passing from Lake Huron into the St. Clair River is approximately 350 mi^2. At the river's entrance, the channel width is approximately 1,000 ft and there is a winter base flow between 150,000 and 180,000 ft^3/s (see Appendix A). The river width in the upper reaches and the main delta channels generally varies from about 1,000 to 3,000 ft, with the midchannel depths ranging from 25 to 50 ft. The St. Clair River proper is approximately 40 miles long, with a total fall of about 5 ft. The single-stem St. Clair River channel above the large delta is about 30 miles long and contains nearly all of the river's fall. The average channel flow velocity varies between 2 and 6 ft/s, but is generally on the order of 3 ft/s. Due to these high water velocities, the St. Clair River generally remains free of ice above the delta.

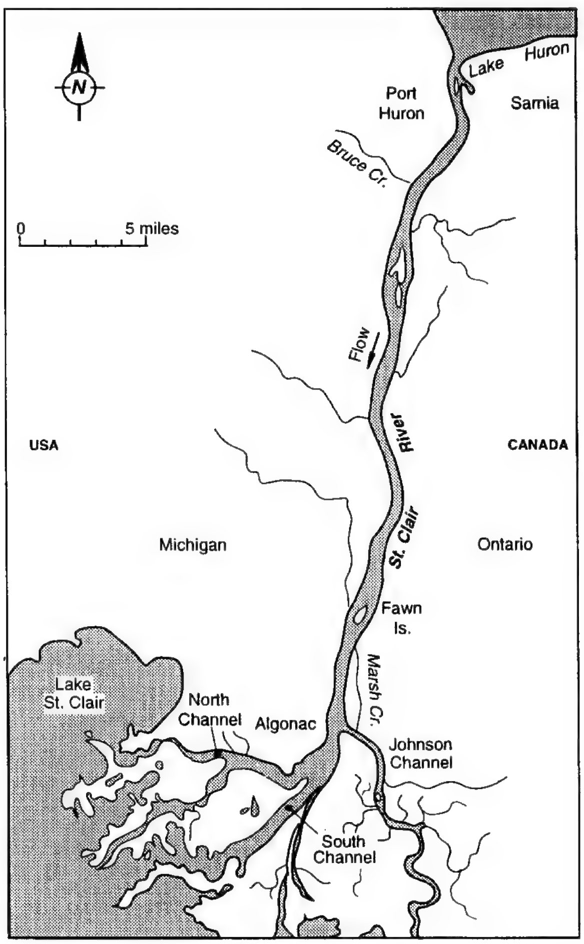

Figure 8. The Lake Erie–St. Clair River confluence, Port Huron, Michigan.

The movement of ice out of the large expanse of southern Lake Huron into the narrow entrance of the river is governed by a complex interaction of ice mechanics, water currents, wind, and shoreline geometry (Daly 1992). Air temperature and wind are the two predominant factors affecting the formation and strength of the ice bridges at the entrance of the river. An initial cold period is needed to produce sufficient quantities of ice to form the arch. Continued subfreezing air temperatures then thicken the ice, making the arch strong enough to resist water current and wind stress. The mean air temperature during the winter months is 35°F, with the lowest monthly mean temperature of 31°F occurring in January. Although the relationship is not fully understood, wind appears to be the predominant factor in the breakup of the ice arch. Stress on the ice cover from strong north winds, along with wave action, can fragment the ice cover and the arch, allowing floes to move downstream into the river. The mean winter wind velocity is 11 mi/h at the confluence, and wind velocity peaks in excess of 50 mi/h can occur during storms.

It is possible that an ice control structure could be designed to both enhance ice arch formation and stabilize the ice arch once formed. Such a struc-

Table 6. Confluence sites selected for detailed analysis.

Confluence and location	*Type*	*Importance*	*Possible structural solutions*
Kankakee-Des Plaines Dresden Island, Ill.	Similar sized rivers	Corps dam at Dresden Island threatened by breakup ice from Kankakee.	Structures to reduce frazil production on the Kankakee to reduce ice volume at breakup.
Missouri-middle Mississippi-Ohio Missouri-Illinois border	Similar sized rivers	Infrequent but severe ice problems due to interaction of weather and discharge trends over several major river systems. Major damages and costs incurred.	Ice retention on the Missouri. Enhanced ice passage on the middle Mississippi.
Salmon-Connecticut East Haddam, Conn.	Smaller into larger river	Tidal backwater of Connecticut River stops the Salmon River ice run, causing residential flooding.	Low-cost ice retention structure upstream of threatened area.
Yellowstone-Missouri-Lake Sakakawea Buford-Trenton, N.D.	Smaller into larger river and backwater from downstream dam	Yellowstone ice jams. The jams progress into the Missouri, flooding farmland. Bed aggradation at head of lake is a factor.	Retain Yellowstone ice until the Missouri is free of ice.
Marseilles Lock-Illinois Waterway Marseilles, Ill.	Lock canal into larger waterway	Brash ice in the 3-mile approach canal to the lock as well as formation of ice jams downstream of the lock exit seriously interfere with barge traffic on the waterway.	Weirs to trap frazil upstream of the lock exit. Shear boom to reduce ice volume entering canal, and ice sluice to prevent massive ice quantities from entering lock.
Aroostook-Tinker Dam pool Fort Fairfield, Me.	River into reservoir	Severe ice damage and ice jam flood damage to property. Loss of life.	Retain Aroostook ice until conveyance through slackwater reach is possible.
Chagrin River-Lake Erie Eastlake, Oh.	River into lake	Recurring ice jam flood damage due to midwinter breakup ice runs encountering the intack lake ice cover.	Ice retention upstream of thickly settled areas.
Lake Huron-St. Clair River Port Huron, Mich.	Lake into river	Wind-driven lake ice enters and jams in the St. Clair River, impeding commercial navigation.	Structural methods to encourage formation of a natural ice arch upstream of the river entrance.

ture would need to retain ice reliably while providing passage for early-season commercial navigation.

The confluence of Lake Huron and the St. Clair River merits detailed examination since the ice problems there have a significant economic impact. Extensive information and data are available, including a time-lapse photography study. Ice arch formation at the mouth of the St. Clair River was also the subject of several physical model studies done in the refrigerated research facility at CRREL (Sodhi et al. 1982, Calkins et al. 1982), and Ice Engineering researchers have visited the site on many occasions.

CONCLUSIONS

Table 6 lists the eight confluence sites selected for detailed analysis and evaluation of structural ice control alternatives. The selections cover a broad range of situations, from ice problems on major rivers and waterways with winter navigation to breakup ice jam flooding of residential property. It is hoped that the range of structural ice control methods to be developed for these specific sites will be equally broad. Ultimately, the experience gained from the site-specific cases will be essential in the development of general design guidelines for structural ice control at confluences.

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APPENDIX A: HYDROLOGIC, WEATHER, AND EVENT DATA FOR EIGHT SELECTED CONFLUENCE SITES

Site 1: Kankakee River–Des Plaines River, Illinois

Hydrologic data

River	*Gage location*	*Drainage area (mi²)*	$Q_{avAnnual}$ *(ft³/s)*	*Month*	$Q_{avMonth}$ *(ft³/s)*	*SD*
Kankakee River	Wilmington, Ill.	5,150	4,259	Dec	4,006	3,382
				Jan	4,497	3,484
				Feb	5,497	3,403
			SD = 1,651	Mar	7,283	4,057
Des Plaines River	Joliet, Ill.	2,093	8,989	Dec	8,730	1,241
				Jan	8,437	834
				Feb	8,712	996
			SD = 789	Mar	9,664	1,145

Weather data

	Precipitation (in.) Momence, Ill.				*Air temperature (°F) Kankakee, Ill.*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	1.34	4.89	2.50	1.66	25	46	36.8	10.9
Jan	0.58	3.32	1.62	1.48	20	45	33.3	11.3
Feb	0.10	1.50	0.71	0.72	26	48	37.0	10.6
Mar	1.62	3.48	2.73	0.98	53	61	48.1	12.3

Event data

				Temperature				
Date	*Location*	$Q_{dailyAv}$ *(ft³/s)*	$Q_{monthPeak}$ *(ft³/s)*	*Min.*	*Max.*	*Ave.*	*Stage*	*Damages*
2/28/82	Kankakee River	23,000	32,000	—	—	—	10.62	$8.2 million
2/23/85	at Wilmington	13,000	45,000	—	—	—	12.83	$1.0 million
2/14/84	gage	33,300	33,300	—	—	—	7.06	$527,000

Site 2: Missouri–middle Mississippi–Ohio River system

Hydrologic data

River	*Gage location*	*Drainage area (mi²)*	$Q_{avAnnual}$ *(ft³/s)*	*Month*	$Q_{avMonth}$ *(ft³/s)*	*SD*
Missouri River near mouth	St. Joseph, Mo.	420,300	41,638	Dec	22,343	11,944
				Jan	19,639	8,910
				Feb	26,571	11,317
			SD = 12,280	Mar	44,766	18,944
Middle Mississippi River near upstream end	St. Louis, Mo.	697,000	187,280	Dec	122368	75,735
				Jan	114,770	61,307
				Feb	142,301	64,202
			SD = 64,826	Mar	232,174	99,492
Ohio River mouth	Metropolis, Ill.	203,000	273,794	Dec	288,603	174,839
				Jan	398,177	218,739
				Feb	464,358	239,077
			SD = 70,980	Mar	519,458	199,003

Site 2: Missouri–middle Mississippi–Ohio River system (cont'd)

Weather data, St. Louis Science Center

	Precipitation (in.)				*Air temperature (°F)*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	0.93	7.44	2.81	1.74	32	51	42.9	12.4
Jan	0.23	4.24	1.92	1.46	25	50	38.8	13.4
Feb	0.52	4.94	1.99	1.38	30	55	43.8	13.3
Mar	1.75	7.41	3.73	1.73	47	63	55.0	13.4

Average monthly flows (ft^3/s) in winters with severe ice problems

Location and month	*1989*	*1979*	*1977*	*1962*	*1958*	*1951*	*1936*
Mississippi River, St. Louis, Mo.							
Dec	—	110,265	60,381	128,794	93,665	60,335	84,674
Jan	—	73,971	48,135	116,058	76,068	73,487	58,803
Feb	—	126,107	73,807	241,321	72,475	158,257	74,310
Missouri River, Kansas City, Mo.							
Dec	—	44,655	31,045	22,619	18,219	17,810	13,554
Jan	—	24,361	20,028	23,826	16,415	25,164	9,125
Feb	—	35,043	26,686	60,096	20,221	28,025	15,728
Ohio River, Metropolis, Ill.							
Dec	—	653,161	182,968	375,322	536,710	495,742	180,084
Jan	—	737,742	168,129	433,968	400,000	580,194	389,000
Feb	—	411,643	176,700	495,178	329,393	726,214	316,931

Weather data for severe ice winters: Mississippi River at St. Louis, Mo.

	December		*January*		*February*	
Year	*Avg. temp. (°F)*	*Total precip. (in.)*	*Avg temp. (°F)*	*Total precip. (in.)*	*Avg. temp. (°F)*	*Total precip. (in.)*
1989	47	3.21	48	2.62	35	1.08
1978	40	3.40	29	0.23	30	0.52
1977	42	1.24	25	3.27	44	2.63
1973	37	4.45	40	1.52	42	0.52
1972	50	7.44	40	0.60	42	1.35
1970	43	2.02	37	0.29	48	0.63

Weather data for severe ice winters: Missouri River at Boonville, Mo.

	December		*January*		*February*	
Year	*Avg. temp. (°F)*	*Total precip. (in.)*	*Avg. temp. (°F)*	*Total precip. (in.)*	*Avg. temp. (°F)*	*Total precip. (in.)*
1989	21	2.59	26	0.74	13	1.04
1984	9	3.82	19	0.27	30	2.28
1982	22	1.09	10	2.14	19	0.98
1979	23	1.44	6	3.19	10	1.09
1978	—	—	10	0.34	11	0.66
1977	17	0.20	—	0.79	—	0.58
1973	21	2.28	19	4.07	24	2.10
1972	31	4.92	17	1.13	21	1.16
1970	24	1.16	14	0.25	21	0.28
1968	27	3.61	16	1.22	20	1.02
1966	32	2.47	15	0.15	21	2.07
1963	21	0.70	10	0.35	18	0.16
1962	20	1.99	12	1.67	25	1.49

Site 3: Salmon River–Connecticut River

Hydrologic data

River	*Gage location*	*Drainage area (mi²)*	$Q_{avAnnual}$ *(ft³/s)*	*Month*	$Q_{avMonth}$ *(ft³/s)*	*SD*
Salmon River near mouth	E. Hampton, Conn.	100	185	Dec	219	131
				Jan	249	169
				Feb	251	118
			SD = 54	Mar	377	131
Connecticut River above confluence	Hartford, Conn.	10,493	16,769	Dec	15,944	5,084
				Jan	13,129	3,900
				Feb	11,818	2,638
			SD = 1,032	Mar	21,937	9,502

Weather data

	Precipitation (in.) Hartford, Conn.				*Air temperature (°F) Hartford Bradley Airport*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	22.2	5.21	3.74	1.50	27	45	37.6	10.2
Jan	3.22	4.99	4.00	0.90	26	42	33.5	10.0
Feb	2.79	4.70	3.71	0.96	26	46	36.7	9.9
Mar	1.33	5.27	3.08	2.01	37	53	46.2	10.6

Event data

Date	*Location*	$Q_{dailyAv}$ *(ft³/s)*	$Q_{monthPeak}$ *(ft³/s)*	*Temperature (°F)* *Min.*	*Max.*	*Avg.*
1/29/94	Salmon River	1,730	1,730	—	—	—
2/1/82	E. Hampton gage	613	2,410	21	43	32

Note : Temperatures are from Hartford Bradley Airport.

Site 4: Yellowstone River–Missouri River–Lake Sakakawea

Hydrologic data

River	*Gage location*	*Drainage area (mi²)*	$Q_{avAnnual}$ *(ft³/s)*	*Month*	$Q_{avMonth}$ *(ft³/s)*	*SD*
Yellowstone River near mouth	Buford, N.D.	70,000	—	Dec	—	—
			—	Jan	—	—
			—	Feb	—	—
			—	Mar	—	—
Missouri River downstream of confluence	Williston, N.D.	164,500	20,405	Dec	10,271	3,439
				Jan	10,040	3,751
				Feb	11,176	4,666
			SD = 4,401	Mar	18,523	6,949

Weather data, Williston Sloulin Airport

	Precipitation (in.)				*Air temperature (°F)*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	0.07	1.43	0.54	0.31	5	37	24.7	14.9
Jan	0.03	1.42	0.55	0.35	-3	34	18.8	16.3
Feb	0.04	1.48	0.43	0.36	12	41	26.4	15.1
Mar	0.01	2.26	0.66	0.45	21	52	38.0	14.5

Site 4: Yellowstone River–Missouri River–Lake Sakakawea (cont'd)

Weather data for severe ice winters, Williston, N.D.

	January		*February*		*March*	
Year	*Avg. temp. (°F)*	*Total precip. (in.)*	*Avg. temp (°F)*	*Total precip. (in.)*	*Avg. temp. (°F)*	*Total precip. (in.)*
1986	30	0.35	21	0.62	50	0.83
1978	8	0.30	17	0.52	39	0.44
1976	22	0.58	35	0.21	36	0.74
1975	24	0.14	23	0.13	33	2.26
1972	14	0.43	18	1.37	37	0.91
1952	14	0.57	26	0.81	26	0.42

Site 5: Marseilles Lock–Illinois Waterway

Hydrologic data

River	*Gage location*	*Drainage area (mi^2)*	$Q_{avAnnual}$ *(ft^3/s)*	*Month*	$Q_{avMonth}$ *(ft^3/s)*	*SD*
Illinois River	Marseilles, Ill.	8,259	10,769	Dec	9,842	4,762
				Jan	10,019	5,149
				Feb	11,591	4,781
			SD = 2,641	Mar	15,173	6,463

Weather data, Marseilles, Ill.

	Precipitation (in.)				*Air temperature (°F)*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	0.33	7.08	2.24	1.42	30	30	30.0	10.6
Jan	0.16	5.05	1.62	1.06	18	33	26.2	13.3
Feb	0.00	2.91	1.42	0.70	31	36	33.3	11.6
Mar	0.20	5.92	2.71	1.36	54	54	53.6	11.8

Monthly discharges, Illinois River at Marseilles, for the severe ice winter of 1985 (ft^3/s)

	January	*February*
Average	11,735	16,581
Maximum	33,300	77,000
Minimum	5,270	4,210

Site 6: Aroostook River–Tinker Dam pool

Hydrologic data

River	*Gage location*	*Drainage area (mi^2)*	$Q_{avAnnual}$ *(ft^3/s)*	*Month*	$Q_{avMonth}$ *(ft^3/s)*	*SD*
Aroostook River	Fort Fairfield, Me.	2,230	3,334	Dec	1,864	1558
				Jan	979	643
				Feb	706	406
			SD = 964	Mar	897	465

Weather data, Fort Fairfield, Me.

	Precipitation (in.)				*Air temperature (°F)*			
Month	*Min.*	*Max.*	*Avg.*	*SD*	*Min.*	*Max.*	*Avg.*	*SD*
Dec	0.82	7.40	3.34	1.56	30	30	29.6	9.2
Jan	0.38	5.52	2.62	1.20	—	—	27.8	8.4
Feb	0.19	5.38	2.43	1.07	19	19	19.2	12.8
Mar	0.52	5.82	2.65	1.15	—	—	—	—

Site 7: Chagrin River–Lake Erie

Hydrologic data

River	Gage location	Drainage area (mi^2)	$Q_{avAnnual}$ (ft^3/s)	Month	$Q_{avMonth}$ (ft^3/s)	SD
Chagrin River	Willoughby, Oh.	246	338	Dec	419	281
				Jan	470	288
				Feb	552	280
			SD = 91	Mar	696	256

Weather data, Willoughby, Oh.

	Precipitation (in.)				Air temperature (°F)			
Month	Min.	Max.	Avg.	SD	Min.	Max.	Avg.	SD
Dec	2.41	3.30	2.89	0.44	41	45	42.7	11.4
Jan	2.05	6.28	4.17	2.99	42	48	44.9	11.6
Feb	1.11	1.29	1.20	0.13	38	43	40.3	8.0
Mar	1.23	4.31	2.22	1.41	43	48	45.2	12.9

Event data

Date	Location	$Q_{dailyAv}$ (ft^3/s)	$Q_{monthPeak}$ (ft^3/s)	Damages
1/28/94	Chagrin River	—	—	$1.0 million
3/14/78	at Willoughby	4,700	4,700	$980,000
1/21/59	gage	10,500	10,500	$110,000
3/21/48		3,360	12,300	$22,000

Site 8: Lake Huron–St. Clair River

Hydrologic data

Confluence	Gage	Drainage area (mi^2)	$Q_{avAnnual}$ (ft^3/s)
Lake Huron	Port Huron, Mich.	—	150,000–180,000
St. Clair River	Port Huron, Mich.	222,400	—

Weather data, Port Huron, Mich.

	Precipitation (in.)				Air temperature (°F)			
Month	Min.	Max.	Avg.	SD	Min.	Max.	Avg.	SD
Dec	0.30	5.33	2.19	1.12	25	43	35.4	9.3
Jan	0.18	4.99	1.74	1.12	20	41	31.0	9.6
Feb	0.12	5.58	1.66	1.18	24	41	33.1	9.2
Mar	0.25	5.10	2.15	0.93	34	49	42.2	10.9

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Andrew M. Tuthill and Anthony C. Mamone

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13. ABSTRACT (*Maximum 200 words*)

This study examines a broad range of ice problems at river confluence sites, grouping the sites into four categories. Weighted criteria were used to select two representative sites from each category for detailed analysis. This report describes the ice problems at the eight selected sites, focusing on the relationship between channel geometry, hydrometeorological factors, and the historical record of ice events. For each site, tentative structural solutions are proposed.

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